

Prevention of Scale on Concrete Pavement Surfaces by Air Entrainment

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One form of concrete deterioration, possibly more prevalent in Michigan and other states with similar climate, is that due to surface scaling and subsequent disintegration from the surface downward. This condition has become more serious as the use of chemical salts for removal of ice from concrete pavements has increased. The unsightliness and roughness of scaled areas, the necessary subsequent maintenance, and the added possibility of further deterioration have been of vital concern to highway engineers for years and the subject of considerable research. This problem has led, within the last decade, to a concerted program of research in which many agencies have participated, including certain federal, state, and municipal departments, as well as individual portland cement manufacturers and the Portland Cement Association. The most significant result of this research has been the discovery of the principle of air entrainment and the application of this principle to construction practice for the purpose of creating more durable concrete pavements.

The results of investigations by the several agencies have demonstrated conclusively that concrete having excellent durability and high scale resistance can be produced by introducing into the concrete mixture a definite quantity of air in excess of that normally found in ordinary concrete. The resulting product is commonly referred to as air-entrained concrete.

It is the purpose of this paper to present the significant facts pertaining to the manufacture and use of air-entrained concrete for scale-prevention purposes based on the results of many studies on this subject and including the experiences of the Michigan State Highway Department.

AIR ENTRAINMENT IN CONCRETE

The principle of air entrainment in concrete consists of the incorporation into the concrete mixture of proper amounts of minute, uniformly distributed, but disconnected air bubbles. Since this introduced air functions differently from the air in ordinary concrete mixtures, it mater-

ially alters the physical properties of both the plastic and the hardened concrete. Freshly mixed concrete containing entrained air is more plastic, possesses better workability, and can be handled with less segregation than ordinary concrete. The hardened concrete has excellent durability with respect to freezing and thawing action and remarkable resistance to scaling caused by the chloride salts used in ice control. Furthermore, surface water or bleeding of the concrete during placing is practically eliminated, thus greatly reducing the time interval between mixing and finishing operations.

Although the entrained air has a definitely beneficial effect on workability and durability, data available at the present time indicate that for each percentage of increase in the amount of air above the amount which exists in ordinary concrete, there will be a reduction in flexural strength of two to three percent and in compressive strength of three to four percent. The strength decreases in proportion to the increase in air content. It is generally accepted that satisfactory scale resistance and durability can be obtained without serious loss in strength if the total air content is maintained between three and five percent by volume computed on the basis of the theoretical weight of air-free concrete of the same proportions. A minimum total void content of three percent is sufficient to assure durability; more than five percent needlessly impairs strength without appreciable improvement in resistance to frost and salt action. Since the air content of ordinary concrete is normally around 1 to 1.5 percent, the increase in void content brought about by the introduced air would correspond to a drop in unit weight of the concrete of from about three to six pounds per cubic foot. The best practice is to keep the air content as low as possible consistent with the results desired.

AIR-ENTRAINING MATERIALS

The air-entraining materials that have been investigated and tried experimentally in varying amounts may be grouped functionally into three general classes: (1) organic compounds of which the inherent foaming action is independent of any subsequent chemical reaction with the cement; (2) other organic compounds which, when added to the cement, react with the alkalis present to produce foaming agents; and (3) gas-generating agents. Some of these compounds may be either inter-ground with the cement or added to the batch at the mixer, while others are of necessity restricted to only one of these two methods of incorporating the air-entraining agent in the concrete mixture.

The first group includes the sodium compounds of certain organic acids found in fats, oils, and resins and the sodium salts of various sul-

fated or sulphonated organic compounds. These compounds are soapy in nature and rely for their effect on the property they possess of weakening the surface tension of water to cause foaming. Examples of this type are Orvus (sodium lauryl sulfate), neutralized Vinsol resin (sodium salt of the resin acids), and Darex, the air-entraining ingredient of the latter being the sodium salt of a still different sulphonated organic compound.

The materials found in the second group are not in themselves air-entraining agents. In order to cause foaming they must be converted to the respective water-soluble soaps through their reaction with the hydroxides of the alkali metals present in the cement. Examples of this type are rosins, flake Vinsol resin, and the various animal and vegetable fats and oils. Here the actual amount of air-entraining material produced will depend not only upon the amounts of these substances added, but also on the amount and availability of the alkali oxides present in the cement. For this reason, air-entraining agents of the first group in general give more consistent and uniform results than those of the second, and their effect is influenced less by the length of mixing time, since the soap-forming reaction progresses as mixing continues.

Both of the above-described groups of air-entraining materials serve to entrap air as such in the mix. Materials of the third group, as their name implies, do not entrap air, but generate gas, usually hydrogen or oxygen, within the mix by the action of inorganic elements or compounds on certain constituents of the cement. The commonest examples of this type are aluminum powder, which produces hydrogen in contact with the alkali hydroxides, and hydrogen peroxide, which is completely decomposed in the presence of these hydroxides to liberate oxygen. The gases so formed seem to accomplish the same purpose as entrained air in promoting durability, and in some cases the use of aluminum powder is of definite advantage in preventing pockets underneath horizontal reinforcing steel caused by water gain, since a slow swelling of the concrete takes place for some time after placing.

At the present time the American Society for Testing Materials has issued tentative specifications concerning the use of Vinsol resin (a product of the Hercules Powder Company of Wilmington, Delaware) and Darex AEA (a product of the Dewey and Almy Chemical Company of Cambridge, Mass.) as air-entraining materials in the manufacture of air-entraining portland cements. The Vinsol resin may be added to the clinker as plain flake resin or sodium resinate in solution or powder form. The sodium resinate of Vinsol resin and Darex may either be added to the batch at the mixer as separate ingredients or interground with the cement at the mill.

Many other materials available have the property of entraining air in concrete and may prove satisfactory if properly used. However, these materials should not be used unless it can be demonstrated through research and experience that they entrain the specified amount of air without impairing the quality of the concrete.

The blending of plain portland cement with a natural cement which contains an interground air-entraining agent will produce a satisfactory air-entrained concrete. The blending is usually performed on the basis of one part natural cement to five parts portland cement.

The introduction of added air into a concrete mixture necessitates changes in mix design and careful control of production if optimum results are to be achieved. Almost every element in concrete making, whether of materials or processes, must now be examined in the light of its effects on air contents and, conversely, the effect of the air content on processing of the mix and the properties of the hardened concrete. For instance, in a given mix, air entrainment will be influenced by the water content, the effect being more pronounced in lean mixes than in rich ones. The amount, character, and grading of both fine and coarse aggregate, the individual properties and amount of cement used, the mixing time, the method of mixing, and the amount and type of air-entraining agent, all affect to varying degrees the quantity of air taken into the mix. In addition, there are encountered, during the process of manufacturing air-entrained concrete in the field, numerous factors that influence the quality and air content of the finished product. Each project becomes an individual problem in concrete-mix design and control which requires much more supervision than is necessary when working with ordinary concrete in order to produce a uniform concrete mixture meeting specified design requirements.

The question of a choice between the use of an air-entraining cement or an air-entraining admixture at the mixer will depend almost entirely on how the engineer wishes to control the work. Each method has its advantages and disadvantages. In either case proper control methods must be provided to insure a satisfactory end product at the mixer.

DESIGN OF MIX

In the design of air-entrained concrete it has been customary only to make certain changes or adjustments in the ordinary concrete mix necessary to insure the specified air content and other desirable properties of the concrete with the least sacrifice in strength.

Methods of adjusting proportions of the mix vary among different users. Features common to all, however, are reduction in water and sand

content. Other adjustments are possible under certain conditions, and no hard and fast rule can be applied to these adjustments.

Mortar tests alone cannot be depended upon to give an accurate indication of the amount of air that will be entrapped in the finished concrete. The air content of a given concrete mix can be determined only on the basis of actual trials with all of the materials to be used. Major adjustments of these trial batches may, for optimum results, require control of other factors than sand content alone. Such tests may reveal a deficit or excessive air content, which would involve too great an adjustment in sand content, and would therefore compel a change of air-entraining cement or the amount of air-entraining agent used as an admixture. Once the mix is designed on this basis, any additional changes could then safely be made by varying the sand content of the mix in the field at the beginning of the job and thereafter as may be necessary under conditions encountered during the progress of the work.

CHARACTERISTICS OF AIR-ENTRAINED CONCRETE

The introduction of well distributed, minute air bubbles into a concrete mix apparently decreases the particle interference of the aggregates, thereby greatly improving the workability of the treated concrete over that of normal concrete with the same aggregates and proportions. The resulting mixture has an extremely fatty appearance similar to that of an oversanded mixture. Segregation and bleeding are practically eliminated. As a result there is little free water on the surface to facilitate finishing operations, and it is therefore imperative that finishing operations be started and completed with a minimum of delay lest drying of the surface hinder proper finishing. Extreme fluctuations in temperature, relative humidity, or wind velocity will influence the finishing characteristics of air-entrained concrete.

Air-entrained concrete is inherently more sticky than ordinary concrete. Consequently, steel-shod floats and finishing tools have proved better than wooden ones. In some cases it may even be necessary to adjust the transverse oscillations of the screed to its forward motion to prevent torn surfaces. Experience has proved that the problems encountered are simply those involved in adjusting construction practice to the characteristics of the new concrete and require no more radical changes than might be necessary because of many other circumstances frequently encountered in job conditions.

CONSTRUCTION PRACTICE

Certain construction procedures must be closely observed in order to derive maximum benefit from the air-entraining materials. Caution must

be exercised in handling of air-entraining cements during batching operations. These cements have a greater tendency to flow in the dry state than normal portland cements, and special precautions should be taken to prevent batch losses due to leakage through cracks and openings of any kind. Handling and proportioning of the aggregates at the batching plant should be conducted in such manner as not to alter too greatly their original grading characteristics and batch weights. The water content of the mixture greatly influences the amount of entrained air and therefore must be carefully controlled within narrow limits. Since the time of mixing is generally fixed, there remain the speed of rotation, the mixing characteristics, and the physical condition of the mixer drum to influence the properties of the mixed concrete. All these factors may be successfully controlled on any project by rigid inspection and proper specifications based upon experience and research.

Calcium chloride in amounts up to the two percent has been added successfully to air-entrained concrete to facilitate paving operations during periods of low air temperatures. Laboratory tests indicate that calcium chloride in amounts up to two percent, when added to the batch either in solution or in dry form, increases early strengths without decreasing the effectiveness of the air-entraining material in entraining air and in providing a high degree of resistance to scaling and to disintegration caused by freezing and thawing action.

Experience also indicates that color pigments made from iron oxides can be used successfully with air-entraining materials without any sacrifice in the strength, durability, or scale resistance characteristics of the concrete.

MICHIGAN'S EXPERIENCE WITH AIR-ENTRAINED CONCRETE

Michigan has been using air-entrained concrete for the past five years as a method of eliminating scale caused by ice-control methods, and a brief description of our experience may be of some interest in connection with the general subject of this paper.

Michigan's experience in the use of air-entrained concrete dates back to the construction of the Michigan Test Road in 1940. A portion of this test road was devoted entirely to a study of the problem of scaling and methods for its control. Factors in the investigation to receive major consideration in relation to scaling were the addition of mineral fillers to supplement the fines in aggregate, proprietary admixtures, air-entraining materials, natural cements with and without air-entraining materials, and finishing and curing methods. Subsequent durability studies revealed that by using air-entraining materials it was possible to

obtain a concrete surface practically 100 percent scale-resistant to chloride salts.

Air-entrained concrete that is cast during the summer construction season may be safely treated with sodium or calcium chloride for ice control the following winter. Attention is called, however, to the damage that will result if air-entrained concrete that was cast during the fall is treated in the following winter. This concrete will not be scale-resistant until the second winter after construction.

When the test road was constructed, two air-entraining materials were available for trial, flake Vinsol resin and a wetting agent called Orvus, manufactured by the Procter and Gamble Soap Company for industrial use. Two Michigan cement manufacturers furnished Vinsol resin portland cement milled from the same clinker respectively as was used in manufacturing the standard portland cements specified for comparative study on the same project. The cement was ground with 0.15 pounds (\pm 20 percent) of pulverized Vinsol resin per barrel of cement added to the clinker at the time of grinding. The specific surface of the cement was specified to be within 1,750 and 2,100 square centimeters per gram. These requirements were furnished by the Portland Cement Association. Measurements of drop in weight in the field showed that this specification gave the desired weight drop of approximately five pounds per cubic foot for the materials used on the project.

The Orvus, procured in paste form from the manufacturer, was dissolved in warm water to form a solution of known concentration. The required amount of the solution per batch of concrete was added to the dry materials at the skip. It was found by experiment that, for the particular materials used, 0.06 pounds of Orvus per barrel of cement gave the desired reduction in weight of approximately five pounds per cubic foot. The concrete mixtures resulting from the use of either of the two air-entraining materials, Orvus and Vinsol resin, possessed similar physical properties characteristic of air-entrained concrete.

The reduction in strength of the air-entrained concrete as compared to the standard concrete was approximately 15 to 20 percent. This marked difference in strength values on the test road may be attributed to the high air content required in the concrete and the lack of basic information in the design, control, and handling of air-entrained concrete at that time.

ACCELERATED SCALING STUDIES

The scale-resistance properties of the respective concrete sections were subsequently evaluated by a series of accelerated scaling studies conducted during the winters of 1940-1941 and 1941-1942.

To accelerate the scaling action of chloride salts, test panels three feet wide and twelve feet long were placed at selected spots on each concrete surface embodying the special feature under consideration. (See Fig 1.) Water was applied to the test area $\frac{1}{4}$ inch deep and allowed to



FIG. 1. Typical installation of test panels used in accelerated scaling studies.

freeze over night. The following morning the ice was melted by distributing calcium chloride over the area at the rate of five pounds per area. When the ice was disintegrated, the slush was removed and the surface flushed. Fresh water was again applied to the test area and the freezing and thawing cycle repeated. At the end of each freezing and thawing cycle, the amount of scale developed during the cycle was determined by superimposing over the test area a grid mesh with twelve-inch openings. Weather conditions permitted a complete freezing and thawing cycle practically every day throughout the duration of the tests.

The air-entrained concretes containing Orvus or Vinsol resin did not scale under these tests, which were considered much more severe than would be experienced from normal de-icing operations. The data in Table I present the relative resistance to scaling of the different concretes at conclusion of the tests. The air-entrained concrete panels did not

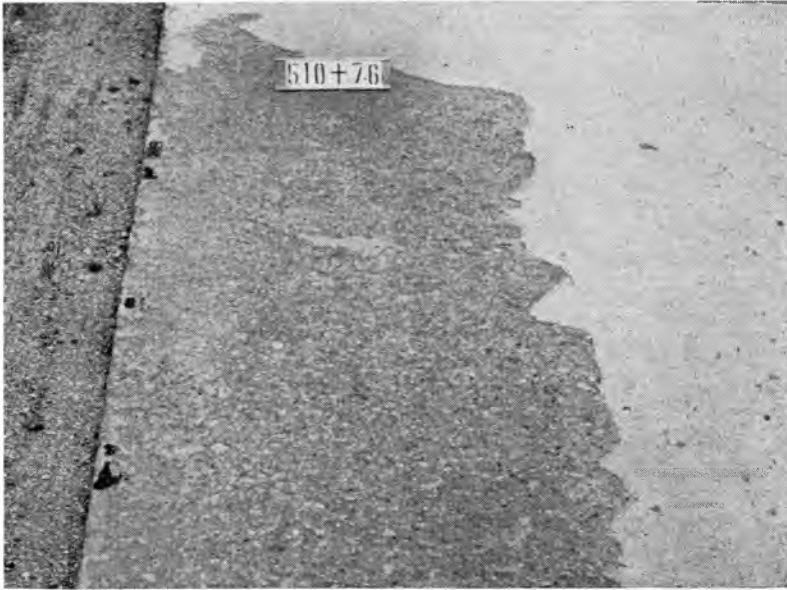


FIG. 2. Typical condition of ordinary concrete after 9 cycles of freezing and thawing, 100 percent scaled.



FIG. 3. Condition of concrete containing Orvus, after 93 cycles of freezing and thawing. No scale.

scale after 93 cycles, whereas 100 percent surface scale occurred on standard concrete after an average of 24 and 22 cycles. (See Figs. 2, 3, and 4.)



FIG. 4. Condition of concrete containing Vinsol Resin after 93 cycles of freezing and thawing. No scale.

DURABILITY STUDIES

Additional freezing and thawing tests on core specimens obtained from the several concrete pavement sections containing air-entraining materials were performed in the laboratory.

At the time of the test the core specimens were 21 months old. The cores were frozen and thawed in water each day until complete disintegration had taken place. Two interesting facts were observed from the test data summarized in Table II. In the first place, the cores from the air-entrained concrete had, with few exceptions, considerably greater resistance to freezing and thawing action than those taken from ordinary concrete; and second, the air-entrained concrete resisted deterioration equally at top and bottom of the core, whereas the ordinary concrete was considerably weaker at the top than at the bottom. The latter phenomenon has for a long time been known to exist in normal concrete pavements. Apparently this inherent weakness can be corrected by the use of air-entraining materials.

TABLE I
COMPARATIVE RESULTS FROM SCALING STUDIES

Air-Entraining Material	Brand of Cement	1940-1941		1941-1942	
		Cycle†	% Scale	Cycle†	% Scale
Orvus	1	33	0	*93	0
Orvus	2	33	0	*94	0
Vinsol Resin	1	33	0	*93	0
Vinsol Resin	2	33	0	*94	0
None	1	33	61	41	100
None	1	13	100	9	100
None	2	21	100	32	100
None	2	27	56	7	100

* 1942 studies continued on panels tested in 1941.

† Number of cycles at which scaling studies were discontinued because of weather conditions or when 100 percent scaling of test panel occurred.

TABLE II
SUMMARY OF RESULTS FROM CORE STUDY

Air-Entraining Material	Brand of Cement	Cycles for Disintegration	
		Top	Bottom
Orvus	1	205	205
Orvus	2	110	200
Vinsol Resin	1	175	170
Vinsol Resin	1	200	200
Vinsol Resin	2	205	200
Vinsol Resin	2	215	200
Standard	1	120	135
Standard	1	120	195
Standard	2	80	110
Standard	2	70	135

NOTE: Results are for individual cores, rather than an average of a group.

AIR-ENTRAINED MATERIALS WITH LIMESTONE AGGREGATES

Further experimentation was carried on using air-entraining materials with limestone aggregates in an attempt to improve the objectionable characteristics of stone sand in concrete, such as bleeding, poor workability, difficult finishing, and excessive scaling. This work was done on Project M75-28, C2, on Road M-94 in the city of Manistique, Schoolcraft County, Michigan, in 1941. Orvus was used as the air-

entraining material and was added at the mixer in specified amounts of approximately 0.05 pounds per barrel of cement throughout the entire project. In part of the project mineral filler was added in addition to the air-entraining material.

It was observed that the introduced air reduced considerably the bleeding so typical of stone-sand mixes and improved the workability of



FIG. 5. Air-entrained concrete in foreground where State construction ends. Ordinary concrete in background.

the concrete over that of regular stone-sand concrete. The added fines in addition to the entrained air contributed materially to the reduction of bleeding and improvement in workability of the concrete mixture. Beam tests indicated that the concrete in all cases was up to specification requirements both for the seven-day and the 28-day periods.

During the following winter, 1941-1942, this pavement was subjected to the same type of accelerated scaling tests as those described previously. At the completion of 66 cycles of freezing and thawing, there was no indication of scaling in either section. A recent inspection, in 1945, revealed that no surface scaling had taken place.

On the basis of the encouraging results obtained from the various test projects in 1941 the Department authorized the use of air-entraining materials in several concrete pavement projects. From 1941 to 1943 approximately 100 miles of air-entrained concrete pavements were constructed. In all this work the air-entraining material was added at the mixer.

The effectiveness of air entrainment in eliminating scale can be found in many cases where projects containing air-entrained concrete abut projects constructed with ordinary concrete. (See Figs. 5 and 6.)

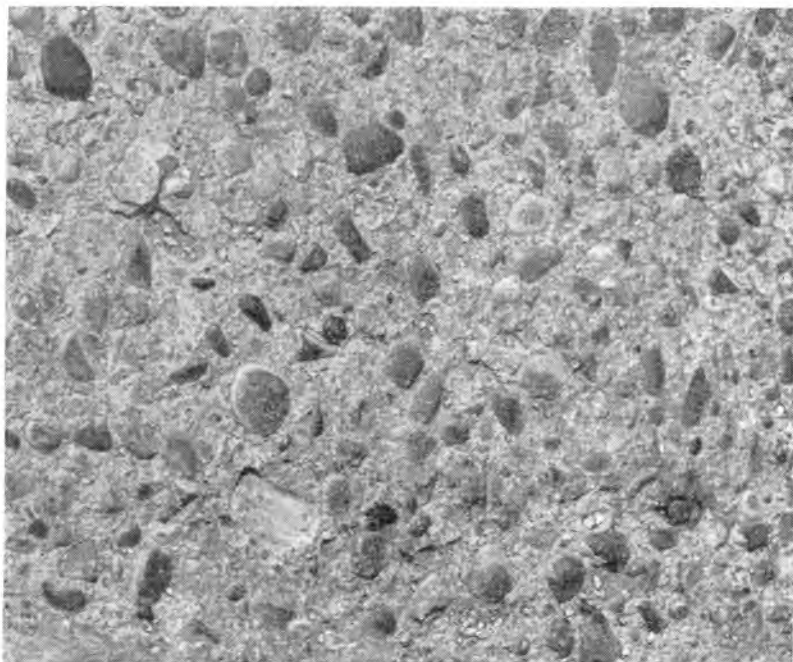


FIG. 6. Closeup view showing exposures of aggregate in concrete which is scaled.

Michigan has a large volume of truck and passenger traffic during the winter months, and it is necessary from the standpoint of traffic safety to eliminate as soon as possible the slippery condition caused by ice and snow on the roads. We have long permitted the application of rock salt with no abrasives on bituminous surfaces without harmful results. Inasmuch as air-entraining concrete could be given this treatment, the question arose as to the minimum age at which concrete pavement constructed without air-entraining agents could be treated with rock salt.

Accelerated scaling tests were run on plain concrete pavement over an age range of four to nine years. Pavements older than six years were not affected. This resistance of the older pavements to scaling is considered to be due primarily to the gradual continuation of the hydration process of the cement, and to the formation of a strong, impermeable, carbonate skin through the reaction of lime compounds in the set cement with atmospheric carbon dioxide. Other external factors, such as deposition of oil films from crankcase drippings, may contribute somewhat to the improved salt resistance of concrete pavements with age.

We are now permitting the use of flake calcium chloride and rock salt for ice removal on all concrete pavement surfaces that are 10 years old or more. The 10-year-age limit was chosen to provide a safety factor because the tests did not cover all the combination of aggregates and cements that have been used.

Provisions for the use of both sodium and calcium chloride with and without abrasives have been thoroughly covered by the Committee on Treatment of Icy Pavements of the Highway Research Board in its published bulletin, *Wartime Road Problems*, No. 9, October, 1944.

In 1943 specifications for Vinsol-resin air-entraining portland cement were officially recognized by the American Society for Testing Materials and by the government. With the advent of air-entraining cement, the practice of adding air-entraining materials at the mixer has practically ceased in Michigan. At the close of the construction season in 1945, Michigan had approximately 150 miles of two-lane pavement containing air-entrained concrete.

It is now generally acknowledged that the use of air-entraining materials in concrete pavements is a distinct step forward in the construction of better highways for the future and indicates the successful solution of just one of the many problems confronting highway administration today. The Department, recognizing the advantages to be gained by this new development, now requires that air-entraining materials be used on all concrete pavement projects constructed under its jurisdiction.